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Interpreting the X-ray Flash XRF 060218 and its associated supernova

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Forty years after their discovery, and in spite of a very large body of observations, the operation of the 'engine' responsible for long-duration Gamma-Ray Bursts (GRBs) and X-ray flashes –as well as the mechanisms generating their radiation– are still the subject of debate and study. In this respect a recent event[1], XRF 060218, associated[2] with SN 2006aj, is particularly significant. It has been argued that, for the first time, the break-out of the shock involved in the supernova explosion has been observed, thanks to the detection of a thermal component in the event's radiation[3]; that this XRF was not a GRB seen 'off-axis', but a member of a new class of energetically feeble GRBs[4]; and that its 'continued engine activity' may have been driven by a remnant highly-magnetized neutron star, a magnetar[5]. I argue, on grounds based on observations and on limpid verified hypothesis, that there is a common, simpler alternative to these views, with no thermal component, no new feeble GRBs, and no steady engine activity.

Many astrophysical systems, such as quasars and micro-quasars, emit relativistic jets. The 'engines' generating 'long' GRBs are the supernovae (SNe) 'associated' with them. The radiation we perceive as a GRB cannot be isotropic, if only because the available energy in a SN event is insufficient. Thus, GRBs must be beamed, and it is natural to assume that the source of their radiation is a jet, emitted by their engine SN. A highly relativistic beam suggests itself for, as a simple consequence of special relativity, its radiation is highly forward-collimated and boosted in energy. The beam consists of a succession of ejecta, for a GRB's radiation typically consists of an aperiodic succession of 'pulses'. Before the interactions with the ambient matter significantly affect it, the ejected matter responsible for a pulse must trace a cone in its voyage, as it freely expands (in its rest system) and moves inertially in space. Up to this point, practically all interpretations of GRBs are concordant[6,7].

Let θ_j be the (half) opening angle of the cone we cited, and let α be the angle, relative to the cone's axis, of a given radiation-emitting point, which moves with the common bulk Lorentz factor, γ, of the emitting region ($\gamma = 1/\sqrt{1-\beta^2}$; $\beta \equiv v/c$). The probability of an observer to be located in the direction α, with a precision $d\alpha$, is $dP \propto \alpha\, d\alpha$. On axis, $dP = 0$. Since $\alpha \leq \theta_j$, dP (whose integral is quadratic) is maximal at the cone's rim, $\alpha = \theta_j$. This is where located GRBs must be concentrated.

The probability to detect events does not vanish abruptly at $\alpha > \theta_j$, since a point's radiation is forward collimated, but not infinitely so. The degree of collimation and the energy boost of the radiation from a given point are dictated by the Doppler factor $\delta(\theta_p) = 1/[\gamma(1-\beta\cos\theta_p)]$, with θ_p the angle between the point's direction of motion and the observer's direction. For $\gamma \gg 1$ and $\theta_p \ll 1$, to an excellent approximation, $\delta(\theta_p) = 2\,\gamma/[1+(\gamma\,\theta_p)^2]$. To be fully precise, I ought to average over the distribution of emitting points[8], but some trivial limiting cases will suffice here.

For observer's directions, θ_{ob}, beyond the cone's rim ($\theta_{ob} > \theta_j$) the point-averaged $\langle\delta(\theta_p)\rangle$ rapidly tends to $\delta(\theta_{ob})$, the limit for a point-like source. The properties of GRBs seen at such angles, for which δ is a rapidly diminishing function of θ_{ob}, are easy to predict. Relative to the average GRB, their 'isotropic equivalent' energy, $E_{\rm iso} \propto \delta^3$, as well as the 'peak energy' of the photons in their pulses, $E_p \propto \delta/(1+z)$, must be small, declining in a correlated way (to be precise, I introduced the effect of the cosmological redshift, z). The time-widths of XRF peaks, $\Delta \propto (1+z)/\delta$ must be relatively large. The peak-to-peak intervals, still relative to GRBs, are not affected; the engine determines them, and it is not moving. Since what I have described are the observed properties of XRFs, it is natural to propose that they are GRBs seen off-axis[9,10], even if the argument is less compelling in the $\theta_j \gg 1/\gamma$ limit. The traditional distinction between XRFs and GRBs is that the former have $E_p < 50$ keV.

I shall assume that XRF 060218, which has all the XRF properties I have described, is also an ordinary GRB seen off-axis. As we proceed, this view will gain support. The opposite view[4] will be discussed anon.

To proceed, we need some observational input. The spectrum of the 'prompt' radiation of GRBs and XRFs is well described by the 'Band' function[11]. For the relatively low X-ray energies of interest here, the first addend of this function, a 'cutoff power-law' (CPL), suffices:

$$E\, dN_\gamma/dE|_{\rm CPL} = a\, E^\epsilon\, {\rm Exp}(-E/E_p), \qquad (1)$$

where E and N_γ are photon energies and numbers, a is a normalization and $\epsilon \sim 0$ is a good approximation case by case, a very good approximation on average[11]. The peak energy of individual photons decreases during a pulse, rapidly tending to $E_p(t) \approx b/t^2$, with b a case-by-case parameter. This correlation between times and energies is better known and studied in its complementary forms:

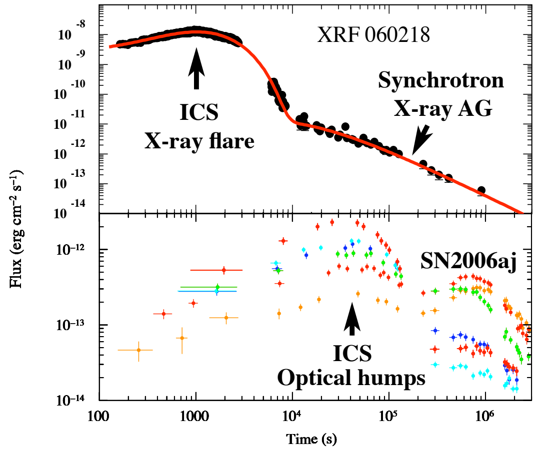

FIG. 1: **(a)** *Upper panel*: the (0.3–10 keV) X-ray flux[3,14,15] of XRF 060218. **(b)** *Lower panel*: the UVOT flux (from Ref. 3), for different UVOT filters (from bottom to top between 10^4-10^5 s): V, B, U, UVW1, UVM1, and UVW2.

the increasing 'lag-times' of the peaks of GRB pulses in decreasing energy intervals[12], and the relation between pulse widths and energy intervals[13], roughly $\Delta \propto t^{-1/2}$. Taking into account the time dependence of E_p, and choosing $\epsilon = 0$, we may expect the spectrum of a particular GRB pulse to be roughly described by:

$$E\, dN_\gamma/(dEdt) = a\, \mathrm{Exp}(-E\, t^2/b). \qquad (2)$$

Having posited that XRF 060218 is but a GRB seen off axis, it behooves me to test whether it satisfies Eq. (2). The X-ray[3,14,15] and optical[3] observations of this single-peak event are shown in Fig. 1. The top part is the X-ray flux in the cumulative (0.3–10) keV interval, fit in a particular model[16], in which Eq. (2) is the approximate expectation[9]. In Fig. 2a, I test the '$E\, t^2$ law' implied by Eq. (2), by plotting (versus energy) the peak times of the optical and UV 'humps' of Fig. 1b, and of their sister X-ray peak, measured in three energy sub-intervals. In Fig. 2b, I show the test of the spectral behaviour of Eq. (2). For lack of space, the three X-ray intervals, whose relative spectrum satisfies Eq. (2), are not shown. Using them as normalization, one can predict the 'peak energy fluxes' (per unit wave-length) in the optical and UV channels, and compare them, as in Fig. 2b, with the observations. The results are fairly satisfactory.

In the standard interpretation[3] of this XRF, a thermal spectrum $E\, dN_\gamma/dE \propto R^2(t)\, E^3\, \mathrm{Exp}[-E/T(t)]$ is added to the CPL spectrum of Eq. (1), with a varying radius and temperature, $R(t)$ and $T(t)$, fit, bin by bin, to the observations. The CPL spectrum masks the tell-tale E^3 thermal dependence. The time dependence of the extracted $T(t)$ is roughly $\propto 1 - t/\sqrt{t^2+\Delta^2}$, which is the expected dependence of $E_p(t)$, to a better approximation than $E_p(t) \propto t^{-2}$, in the model I have quoted[9].

Had Campana et al.[3] used a time-dependent $E_p(t)$, they would have obtained the results in Fig. 2, and, I

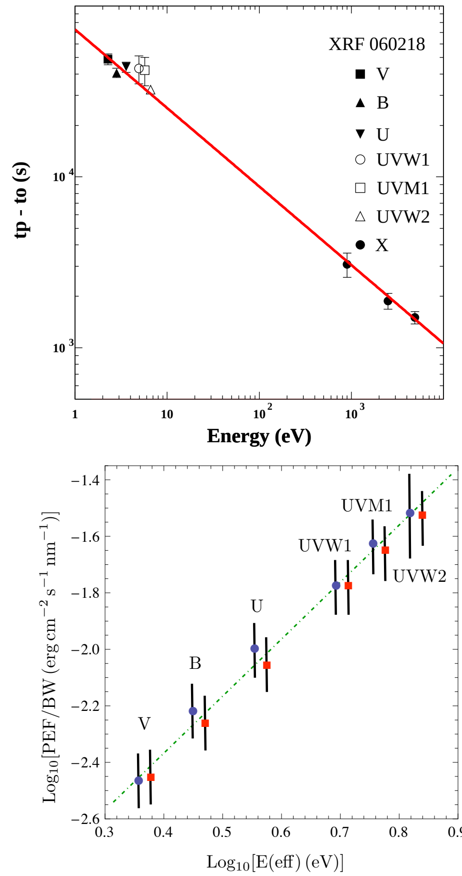

FIG. 2: **(a)** Comparisons of Eq. (2), with data corrected for extinction[16]. *Upper panel*: The '$E\, t^2$ law', with t_p–t_0 the peak position at various energies and t_0 the common peak start-time at all E. The line is the expected $t_p - t_0 \propto 1/\sqrt{E}$. **(b)** *Lower panel*: The spectral dependence. Data and predictions are slightly shifted, to avoid superposition. At UVOT energies, the exponential in Eq. (2) is ≈ 1 and $d\,\mathrm{PEF}/d\lambda \propto E^2$, the dashed line, whose normalization is fixed by the X-ray data.

presume, concluded that a thermal component is unnecessary. These authors cite Amati et al.[4] for the assertion that XRF 060218 is not a GRB seen off axis, but a representative of a new class of sub-energetic GRBs. Presumably that is why what is known about $E_p(t)$ in 'normal' GRBs was not judged to be relevant.

Amati et al.[4] base their cited conclusion on the following fact. If one makes a scatter log-log plot of the E_p values versus total fluence[17] of a collection of GRBs, one finds that they fall, with not much scatter, close to a straight line. A similar result is obtained[18] for a log-log $[(1+z)\, E_p, E_{\rm iso}]$ plot of GRBs of known z, the 'Amati correlation'. These results are 'phenomenological', the lines' slopes and normalizations are fit to the results.

To understand the origin of the correlations between 'prompt' observables, such as E_p and $E_{\rm iso}$, one must specify the radiation mechanism. Let us posit that it is inverse Compton scattering (ICS) of 'ambient' photons by the electrons in a GRB's jet[19], as verified in Ref. 9. In that case, the δ-, *and* γ-dependences of E_p and

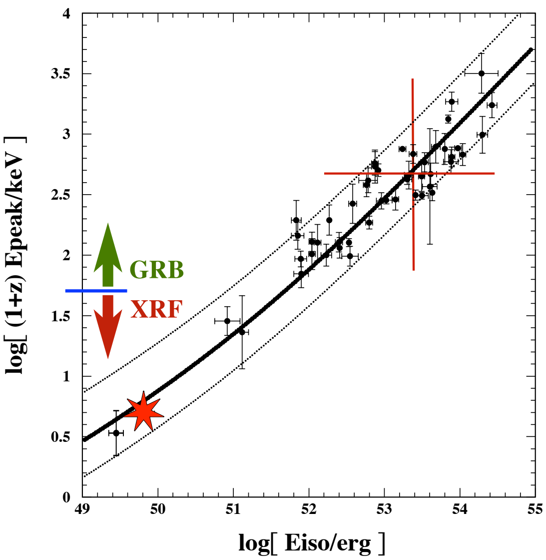

FIG. 3: The $[(1+z)\,E_p, E_{\rm iso}]$ correlation[8]. XRF 060218 is the star. The cross marks the average expectation for GRBs[9].

$E_{\rm iso}$ can be specified. For a point-like source, they are[9] $(1+z)\,E_p \propto \gamma\,\delta$ and $E_{\rm iso} \propto \delta^3$. Since δ decreases, at fixed γ, by orders of magnitude as θ_{ob} increases, and γ cannot be much smaller than 'typical' (for otherwise we would not be observing a GRB or an XRF), we conclude that the case-by-case variability is dominated by δ. Thus, we expect $(1+z)\,E_p \propto (E_{\rm iso})^{1/3}$. Since we used the point-like limit, valid for large θ_{ob}, this result is for XRFs.

In the opposite extreme at which a GRB is seen at an angle $\theta_{ob} \ll \theta_j$, the integration over the source's radiating points masks the dependence on θ_{ob}, so that the 'effective' averaged Doppler factor[8] becomes $\delta \propto \gamma$. Thus, for hard GRBs, $(1+z)\,E_p \propto \gamma^2$ and $E_{\rm iso} \propto \gamma^3$, implying that $(1+z)\,E_p \propto (E_{\rm iso})^{2/3}$. Since the observer's angle varies continuously, we expect[8] the XRFs and GRBs to lie, in the $[(1+z)\,E_p, E_{\rm iso}]$ log-log plane, close to a line whose slope varies smoothly from 1/3 to $\sim 2/3$. This is tested in Fig. 3. The crossing lines are the predicted average values for GRBs, for the advocated origin of the target light that is Compton up-scattered[9]. XRF 060218 is the star in Fig. 3. Incidentally, the above reasoning also explains the observed correlations with (or between) other prompt observables: peak luminosity, lag-time, rise-time and variability[8]. GRB 980425 is an out-lier from correlations involving E_p, its 'second E_p', due to ICS by electrons scattered by the jet[20], is what was observed.

We have been led to conclude that XRF 060218 *is* a normal GRB seen off-axis, among other reasons, *because* it satisfies the correlation we discussed. Amati et al.[4] conclude that XRF 060218 *is not* a normal GRB and *is not* seen off-axis, *because* it lies in a similar correlation. This logical inconsistency, I believe, has a purely logical origin. Their argument[4] is the following: GRBs are seen close-to-axis, GRBs satisfy the Amati correlation, XRF 060218 does it as well, so this object is seen on axis and, since it has very low E_p and $E_{\rm iso}$, it belongs to a new class. My critique of this logic is that, as I argued at the beginning, GRBs are not seen on axis, but on-edge. Since the opposite premise is tacit in Amati et al.[4], one cannot be sure this interpretation of their logic is correct.

In the X-ray flux shown in Fig. 1a, there is a 'plateau' tail labeled 'Synchrotron Afterglow', fit, as the rest of the curve, to a given model[16]. The whole curve has a 'canonical' shape, sketchily seen long ago in GRB 980425, and nine others GRBs[21]. The X-ray and radio afterglows (AGs) of GRB 980425 were attributed to a non-relativistic shock[22,23]. Alternatively, since they coincide with the expectation for an off-axis relativistic jet of an otherwise normal GRB, they were attributed to the jet[21,24]. A large fraction of the X-ray AGs recently observed by Swift and other satellites are 'canonical'. Their plateau phases are, as in the case[5] of XRF 060218, attributed to a continued engine activity[25], perhaps driven by a magnetar remnant[5,26]. In the alternative view, once again, the plateau is due to the moving jet[27]. The difference between these views may be important, not only because of the different underlying GRB theories, but because of its implications on the associated SNe. Suffice it to imagine[21,24] that the X-ray and radio emissions attributed to a SN were actually emitted by a relativistic jet having long departed from the SN location.

The algebra required to discuss GRB afterglows is a bit longer than the one I have been using. For this reason, I shall next state some results with citations, but no proof. The 'alternative view' I repeatedly quoted[9,21] does not require, so far, any conceptual changes or additions, as it confronts the data. The steady 'continued engine activity', for instance, is instead the inevitable inertia of the relativistic jet, its ending 'break' occurring when the interstellar medium begins to significantly decelerate the jetted material[21]. The rapidly-varying spectra of X-ray light curves, as well as the plethora of different Swift light-curve shapes, with and without 'breaks', were not unexpected[28,29]. In the realm of 'fireball models', very many novel phenomena –other than the shock break-out, the steady engine activity, and the subenergetic GRBs that I have discussed here– have been invoked to understand GRBs and XRFs. To each of these phenomena, the 'other view' I have often cited –*the Cannonball Model*– offers a simpler alternative. And it is always the same.

Ab initio, the 'firecone' and cannonball models differed in almost all respects: supernovae as engines (debated *vs* assumed), the substance of the ejecta ($e^+\,e^-$ pairs *vs* ordinary matter), the role of shocks (decisive *vs* absent), the mechanism of γ-ray generation (synchrotron radiation *vs* ICS), to name a few[6,7]. One difference still remaining underlies the conflicting views I have discussed. It is the jet's initial opening angle, θ_j: a few degrees (as in radio images of quasars), *vs* ~ 1 milli-radian. Moreover, a $\theta_j(t)$ that increases with time, *vs* one that eventually decreases. The last and apparently[9,21] surprising feature –a jet that does not expand– is observed in sharper (X-ray) images of quasars, e.g. Pictor A (Ref. 30).

The fraction of SNe that are associated to GRBs and XRFs is $\propto\theta_j^{-2}$, differing by ~ 300 for a one degree *vs* a one milli-radian angle. For $\theta_j \sim 1$ mrad the fraction of SNe associated with GRBs is, within rather large 'cosmological' uncertainties, close to *all* Type Ic SNe[9,21], very far from the standard view[14]. This is one more reason why the opening angle is so decisive. The value of θ_j adopted in the cannonball model corresponds to $\theta_j \sim 1/\gamma$, i.e. to the cone swept by a object which, in its rest system, expands at the speed of light, or of relativistic sound ($c/\sqrt{3}$), and is moving with the typical initial $\gamma \sim 10^3$ required by the data[9,21]. For the same reason, the quest for simplicity, the original fireball models had spherical symmetry[6]. The correct answer must lie in between these two extremes, surely closer to the former than to the latter.

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